A SMART CONTROLLER FOR WIND ELECTRIC WATER PUMPING SYSTEMS

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ABSTRACT

More and more wind electric water pumping systems are replacing the mechanical windmill for irrigation of crops and watering livestock because the electric systems are more efficient, offer the flexibility to site the turbine some distance from the pump, and require little routine maintenance. The motors and pumps used in most pumping systems were designed to operate at a constant rotational speed. However, the wind electric system operates at variable speed because the electricity generated by the wind turbine is variable frequency. Since the wind turbine operates over a wide range of wind speeds, a controller is needed to maintain stable conditions and improve the system efficiency. Experience of the past ten years with water pumping systems at USDA-Agricultural Research Service (ARS), Bushland, TX, has shown that the wind pumping system operates best when the nameplate voltage to frequency ratio (V/f) is maintained. Using this principle, a smart controller has been designed, built and tested by USDA-ARS and the Alternative Energy Institute, West Texas A&M University for wind electrical pumping systems. Earlier controllers used only the frequency or the voltage to determine the cut-in and cut-out points when electricity from the turbine was connected to the load. This new controller also samples the voltage and calculates the ratio of voltage to frequency. Any abnormal conditions, such as current overload, overheating of generator and loss of one or more phase will drive the V/f ratio below a programmed set point and the controller will disconnect the load and protect the generator and motor from being damaged. This inexpensive controller can allow the pumping system to operate in high wind speed conditions with little risk of damaging the pump motor or wind turbine generator.

INTRODUCTION

The increasing age of many of the traditional windmills has resulted in increased maintenance costs and in many instances, a need for replacement. The utility independent wind electric water pumping system offers a number of advantages over the mechanical windmill and is being used to replace them for irrigation of crops and watering livestock. The wind electric system is more efficient, offers the flexibility to site the turbine some distance from the pump and requires less routine maintenance. At a comparable system cost, the wind electric system can potentially pump twice as much water (Clark and Mulh, 1992).

The wind electric system consists of a wind rotor mounted to a permanent magnet generator that produces 3-phase variable voltage, variable frequency electricity. The electricity flows directly from the generator to the pump motor through a relay that is activated by a controller. Since the voltage and frequency of the generator is directly proportional to the wind speed, the electricity causes the pump motor to operate at variable speed. The system uses conventional submersible motors and pumps designed for a constant frequency and voltage. Experience of the past ten years with water pumping systems at the USDA-Agricultural Research Service (ARS), Bushland, TX, has shown that these motors can be operated with variable frequency and variable voltage power within limits. The system performs efficiently as long as the nameplate voltage to frequency ratio (V/f) is maintained (Clark, 1994). The controller is the key system component and is necessary to connect the motor and pump (load) only when the turbine can provide enough power to start and operate the load and to disconnect the load when the power is too great in order to protect the motor and generator.

Two small electrical wind pumping systems, 1000 W and 1500 W were tested by USDA-ARS, Bushland, TX. Each system was operated at several pumping depths and the performance evaluated for over 700 hours of operation at each pumping depth. The controller designed for the 1000 W system was rather simple. It consisted of less than 10 components. The controller performed reliably in low and moderate wind speeds. When the output voltage of the generator reached about 100 V which was enough to energize a relay, the motor and pump were energized and the system started to pump water. When the output voltage of the generator was below about 70 V, the relay was released and the load cut off and the system quit pumping. These set points were not adjustable. The controller had no control functions at high wind speeds, allowing the system to continue pumping. When the wind speed was higher than 16 m/s, the turbine furled vertically to limit the maximum output power to prevent overloading the motor or generator. At times, however, the load current exceeded the rated current. Operating above the rated current causes the wire insulation to deteriorate quickly and is a primary cause of motor burnout. When the operating current exceeded the rated current, it would have been better for the controller to disconnect the motor instead of relying solely on the furling action of the turbine.

The controller designed for the 1500 W was a more complex and costly controller. It monitored the generator frequency and had both low and high frequency cut-in functions as well as low and high frequency cut-out functions. It also monitored current and had a high current cut-out function. When the current went above the overload current setting, a thermal overload switch tripped. This system allowed operation at high wind speeds, but had less risk of damage to the motor or generator. The cost of the controller was high because of the cost of the thermal overload switch and other necessary electronics. Since the cost of this controller was more than one-fourth of the cost of the whole system, it was not desirable for use on a small system.

SMART CONTROLLER

The ideal controller for a wind electric water pumping system would be inexpensive, flexible, maximize system efficiency and provide protection for both the pump motor and the turbine generator. A smart controller was designed and built in an attempt to fulfill these requirements. The controller monitors voltage and frequency and calculates V/f ratio and its operation is based on the following strategy.

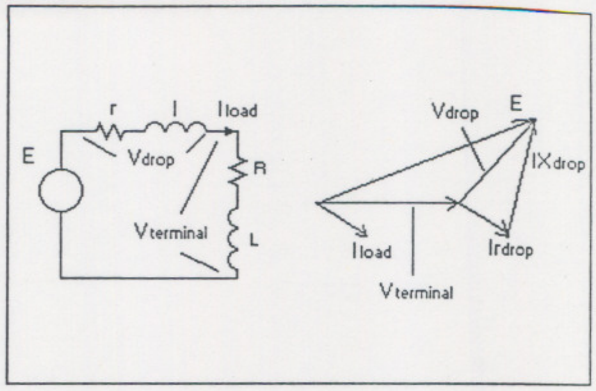

Figure 1. Phasor diagram of wind-electric water pumping system.

The voltage sampled is the generator terminal voltage. It equals the electrical potential of the generator minus the voltage drop inside the generator vectorially. Figure 1 shows the relation among these three vectors.

$$V_{terminal} = E - V_{drop} \qquad [1]$$

where E is the electrical potential of the generator and is proportional to the rotor speed or frequency.

$$E = C f \qquad [2]$$

where C is a constant and f is the frequency. V_{drop} is equal to the product of load current and sum of the interior resistance and synchronous reactance of the generator.

$$V_{drop} = I_{load} * (r + j 2 \pi f L) \qquad [3]$$

where r is interior resistance and L is the synchronous reactance of the generator. So the terminal voltage is equal to the product of a constant and frequency minus the product of load current and sum of the resistance and synchronous reactance of the generator.

$$V_{terminal} = C f - I_{load} * (r + j 2 \pi f L) \qquad [4]$$

When both sides of above equation are divided by the frequency, the following equation results

$$V_{terminal}/f = C - I_{load} * (r + j 2 \pi f L)/f. \qquad [5]$$

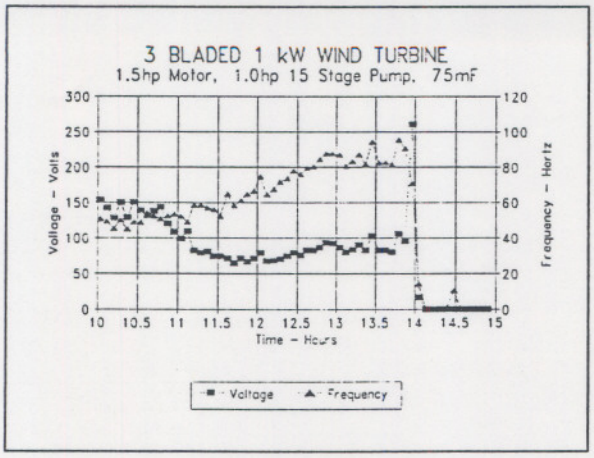

Figure 2a. Measured voltage and frequency from a 1000 W wind-electric pumping system.

At a given frequency, as I_{load} or r increases, the ratio of voltage to frequency (V/f) becomes smaller; therefore, managing the V/f ratio not only takes care of the load current, but also takes care of the interior resistance of the

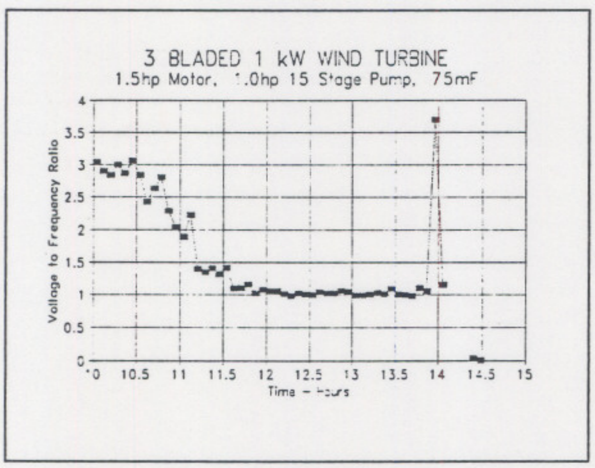

Figure 2b. Measured voltage to frequency (V/f) ratio from a 1000 W wind-electric pumping system.

generator. The system will stop pumping only when the product of current and interior resistance goes high. It is possible after a long period of operation in hot weather for the turbine generator temperature to go high and cause the internal resistance to go high, even if the current is still under the rated amount. This condition can potentially damage the generator. Figure 2 is the voltage, frequency and V/f ratio verses time for an electrical water pumping system tested at USDA-ARS. The system operated at a low V/f ratio (less than 3) for more than seven hours and finally the generator burned out at 1400 hours. These data demonstrate that only using voltage or frequency as the input signal of the controller is not satisfactory for the safety of the system. When the smart controller determines a ratio that is much less than the nameplate value (this number can be key programmed in), it will disconnect the pump motor and protect the generator and motor from burning out. The needed set point value of V/f ratio will depend on the configuration of motor, pump, generator and pumping depth. During cold weather, or when the system just starts to operate in high wind speed conditions, the smart controller lets the system continue pumping. Even if the current goes above the rated current, if the internal resistance is still low, and the generator temperature is still low. It is desirable to let the system work in this way in order to improve the overall system efficiency, especially in gusty wind conditions.

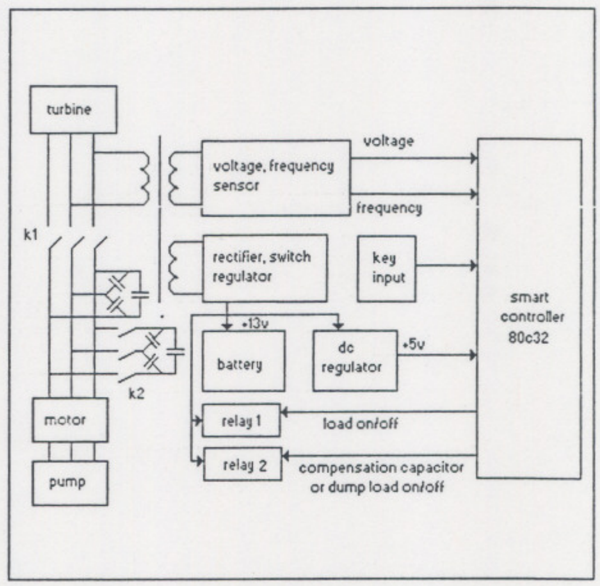

Figure 3. Block Diagram of smart controller for wind-electric pumping systems.

The controller is based on a single chip computer, the model 80c32 microcontroller which is part of the 8051 family of microchips. The 80c32 has 3 internal timers, 6 interrupts and 256 bytes of internal RAM. These hardware resources were sufficient for designing the controller for the wind-electrical pumping system. The input signals to the controller are the frequency and voltage output of the generator. These two signals come from a special power supply transformer connected the generator high voltage phase wires. Figure 3 is the system block diagram.

This controller calculates the ratio of voltage to frequency. Any abnormal conditions, such as overload, overheating of the generator and loss of one phase will drive the V/f ratio down and the controller will cut off the load and protect the generator or motor from burnout. The following parameters can be set using four program keys:

a) Low wind speed cut-out frequency for load (30 Hz; as an example)
b) Low wind speed cut-in frequency for load (40 Hz)
c) High wind speed cut-in frequency for load (70 Hz)
d) High wind speed cut-out frequency for load (90 Hz)
e) Cut-in frequency for dump load or compensate capacitors (70 Hz)
f) Delay time for load (5 sec)
g) Delay time for dump load or capacitor (15 sec)
h) Cut-out voltage to frequency ratio (2.5)
i) Time: second, minute, hour, day, month, year, weekday

The function of delay time for the load is to prevent frequent motor on and off sequences during gusty wind conditions. When the frequency reaches the cut-in set point, and after the delay time during which the frequency always equals or exceeds the cut-in set point, the load will be switched on. Reducing the number of on/off cycles should extend the life of the relays, motor and other electronic components.

Installation of a correct size AC capacitor will improve the system performance dramatically (Muljadi, et al. 1995) (Vick and Clark, 1995). For the 1500 W wind-electric pumping system, the optimum size of the compensation capacitance is 60 μf for the full range of wind speeds. When the wind speed gets too high and the turbine produces more power than the pump load needs, a dump load can be switched in to consume some of the excess power. For the 1000 W generator, the optimum size for compensation capacitance is 30 μf when the wind speed is below 13 m/s, and 45 μf when the wind speed is above 13 m/s (Vick and Clark, 1995). The cut-in frequency set-point for dump load or compensation capacitance determine when to connect the compensation capacitors or the dump load for the different systems.

Other advanced control options used in this controller are power down and watch dog modes. The controller will go into a power down mode when the frequency drops below 10 Hz or the battery voltage drops below 10 volts. In the power down mode, the controller consumes less than 0.1 ma; making it ideal for stand alone systems which uses a battery to power the controller when there is no wind. The built-in watchdog resets the controller if the controller gets into an unpredictable state. This automatic reset function is important for stand alone systems that are often at remote sites and would otherwise be shut down waiting to manually reset.

SOFTWARE

The software for this controller was written in assembly language to provide the fastest possible operating time. The program is in two parts and requires about 4K bytes of memory. The main routine initializes timer one and timer two and defines the interrupt priority. It then goes into a loop that updates the LCD display showing the generator voltage and frequency; V/f ratio and battery voltage and then visits the keyboard. If the program finds a key has been activated, it will go into the key service subroutine where the various parameters can be set. All key set functions can be displayed on the LCD. The second part of the program is the interrupt subroutine which determines the output voltage and frequency of the generator, V/f ratio and battery voltage. Based on the frequency and V/f ratio values and the set points, this subroutine decides the on/off condition of the load.

SUMMARY

The controllers used in two stand alone wind electric water pumping systems were both found to have deficiencies. One was very simple and reliable but lacked adequate safeguards during high gusty wind conditions. The other was a more complex controller that monitored current and frequency and provided overload protection but was found to be too expensive, especially for small wind electric pumping systems. Based on the experiences of operating wind-electric system for 10 years, neither controller was satisfactory for many wind pumping conditions that were encountered. A new smart controller was designed based on a single chip computer, the 80c32 microcontroller, and provides protection to the wind turbine generator as well as the pump motor. It provides a programmable time delay to reduce unwarranted stops and starts in gusty wind conditions, is low in cost and increases the overall system efficiency.

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